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Θ^+: Another Explanation and Prediction

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Abstract

Recently the so-called Θ^+ resonance has been reported first from SPring8[1] and many following experiments showed apparent confirmation of the state. Since Θ^+ exclusively decays into either K^+n or K^0p, it is explained as the predicted pentaquark state which includes $uudd\bar{s}$ quarks. However, one yet has to obtain consistent picture of Θ^+ and its quantum numbers. We try to explain Θ^+ in a conventional picture and show that such picture leads to new predictions on kaon and pion system.

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TABLE I: Spin, parity and isospin of two particle subsystems.

	Θ^+ ($K\pi N$)	πN	KN	$K\pi$
$J\pi$	$1/2^+$	$1/2^-$	$1/2^-$	0^+
I	0	1/2	1	1/2

In this letter we would like to present some remarks on the recently observed new exotic particle Θ^+. We show that our picture leads to further exotic prediction which experiments have likely been missing so far. First let us briefly summarize what have been observed and can be assumed. Θ^+ was observed as a sharp peak at around 1540 MeV in the invariant mass spectrum of both K^+n and K^0p [1, 2, 3, 4]. The width is probably narrower than 10 MeV. Its spin parity is $1/2^+$ according to original prediction by Diakonov [5]. Another property is that Θ^+ seems to be observed only in charge +1 state which indicates that its isospin is 0. Although no assignment on spin, parity and isospin have been given experimentally, it would be worth and interesting to consider what would be derived from the existence of Θ^+ with such properties.

These properties suggests us a conventional picture of Θ^+ as a bound state of $K\pi N$. The masses of the three constituent particles are 1568.2 MeV for $K^+\pi^0n$, 1570.9 MeV for $K^0\pi^0p$, and 1576.8 MeV for $K^0\pi^+n$, respectively. The Θ^+ is at roughly 30 MeV below the threshold. The binding energy of 30 MeV is quite suggestive to consider Θ^+ as a bound state. It is not extraordinary since $\sim$ 10 MeV par particle is typical in nuclei. Question is whether the interactions among K, π and N could realize the bound state. We assume that Θ^+ has $J^\pi = 1/2^+$ and $I = 0$ which are then quantum numbers of the $K\pi N$ system. It is natural to consider that the three particles are in an s-wave to realize the lowest energy state. Then J^π of the $K\pi N$ system is equal to $1/2^+$. Accordingly, spin, parity and isospin of any two particle subsystems are uniquely determined. They are shown in table 1. The nice feature of the three body bound state is that the narrow width of Θ^+ can be naturally explained. Since Θ^+ decays into KN, a pion has to be absorbed either in a nucleon or a kaon to decay. The pion cannot be absorbed in the kaon because 0^+ of the $K\pi$ system does not match 0^- of the kaon. If one allows the $K\pi$ system to have relative angular momentum, the spin-parity can be 1^-, 2^+, 3^-, and so on. Therefore this mismatch cannot be resolved even though non-zero relative angular momentum is introduced. The pion can be absorbed in the

nucleon only when relative angular momentum of the πN system be excited from s-wave to p-wave to make $J^\pi = 1/2^+$. This excitation requires the kaon be excited in relative p-wave with respect to the πN system simultaneously. The decay can thus take place through weak mixing of p-wave.

Such an admixture is seen in the deuteron. It has a d-wave component which is an-order-of magnitude smaller than the dominant s-wave one. It is due to the tensor interaction between nucleons. In the deuteron case total spin 1 allows the two nucleon system to have both s- and d-wave components simultaneously. However, in the Θ^+ case, introduction of p-wave in the πN system is possible only when the kaon is also excited in p-wave with respect to πN system. Thus it is strongly suppressed. Since Θ^+ is a $K\pi N$ bound system in our view, it is an object much more extended than the typical strong interaction range. The excitation to p-wave can take place only when particles are within the interaction range. Thus the decay is further suppressed. Later we give an order-of-magnitude estimate of the width.

We calculated the $K\pi N$ system based on two body interactions for all three channels shown in table 1. The KN and πN scattering have been studied and they are summarized in phase shift analysis [6, 7, 8]. The $K\pi$ interaction was derived from the reaction to produce the two particles simultaneously since both kaon and pion are unstable particles [9]. In a calculation we used separable potential to reproduce the available phase shifts at low energy region. We were not able to find any bound state. We recognized similar attempt to explain Θ^+ as a bound state of the three particles where, however, no bound state was demonstrated to exist [10, 11]. The πN channel (I=1/2) and $K\pi$ channel (I=1/2) are weakly attractive and KN channel (I=1) is weakly repulsive. The attractive interactions are too weak to realize the bound state. The scattering lengths are $\sim 0.18 m_\pi^{-1}$ for πN(I=1/2) [12], $\sim -0.21 m_\pi^{-1}$ for KN(I=1) [13] and $\sim 0.33 m_\pi^{-1}$ for $K\pi$(I=1/2) [9]. These are roughly an-order-of magnitude smaller than that of nucleon-nucleon interaction. We think that it is difficult to reproduce the 30 MeV binding energy with two body interactions currently available.

In the present calculation we used two body interactions which explain low energy scattering data. Extraction of two body interaction at very low energy region is difficult if an unstable particle is relevant. It is particularly difficult when both particles are unstable since assumed production mechanism of the two particles dominantly determines the interaction. Thus we think $K\pi$ interaction has much more room to be modified than that of KN and

πN. We thus considered the case that two body interactions for KN and πN are fixed and that of $K\pi$ is set free.

We think that two body $K\pi$ interaction has to be very strong in order to reproduce binding energy of 30 MeV. It is so strong that the $K\pi$ system has a bound state. As far as we take into account two-body interactions in the $K\pi N$ system, there will be no bound state, if the $K\pi$ system has no bound state. Therefore, the idea of Θ^+ as the $K\pi N$ bound state strongly suggests a possible existence of the bound state in the $K\pi$ system. In other words a search for a bound state in the $K\pi$ system will provide us a key to answer the question on the nature of Θ^+. Let us call this presumed particle X which yet has to be searched for.

We do not give a prediction of binding energy of X since it is already constrained in a region which is narrow enough for the experimental search. If X exists as a bound state, its binding energy has to be within a range of 0-30 MeV otherwise Θ^+ decays into a X and a nucleon. Its spin parity is 0^+ and $I = 1/2$. Since the state consists of only mesons, the charge conjugation leads to the existence of both $K\pi$ and $\bar{K}\pi$ systems. Therefore X^+ and X^0 and their antiparticles X^- and $\bar{X}^0$ exist. The prediction of X as the $K\pi$ bound state is very exotic and hard to believe although we would like to point out that such possibility has not been completely ruled out. We also would like to present an experiment to search for the state or to rule out this possibility.

One wonders that even though X may possibly exist why it has escaped our experimental study. Let us start our discussion on decay properties of X. A particle with strangeness that is lighter than X must be a kaon. Since emission of a pion in addition to a kaon is energetically forbidden, no decay by strong interaction can take place. On the other hand, X can decay by the electromagnetic interaction. Particles possibly present with a kaon in the final state are γ's and e^+e^- pairs. The $X(0^+) \to K(0^-)$ transition constrains particles in the final state. The $X \to K\gamma$ decay is forbidden because of angular momentum conservation. The $X \to Ke^+e^-$ decay is forbidden because the electromagnetic vector current doesn't have an axial charge. Therefore the $X \to K\gamma\gamma$ decay is the lowest order decay mode. Lifetime is then expected to be that of π^0. This decay mode makes it very difficult to identify X by experiments. Two γ's from the X decay make no peak in the invariant mass distribution. Usually m_{π^0} region is selected in the invariant mass distribution of two γ's to make further hadron spectroscopy and this procedure leaves no chance to search for X. Detection of γ

rays is usually difficult since γ-ray detectors are subject to backgrounds and loss of signal due to energy escape from electromagnetic shower in the detectors.

One has to search for a peak corresponding to X in an invariant mass distribution of $K\gamma\gamma$ channel which appears to have not been attempted with appropriate reactions. X is produced in reactions where kaons and pions are abundantly present. Also since X is an extended object, soft or relatively low momentum transfer reaction is needed to fuse a kaon and a pion into X. Kaons and pions are abundantly present in relativistic heavy ion reactions. Despite small coalescence probability, X may have been produced in the reactions although optimized measurement or analysis are probably necessary.

We can predict properties of X by its size which is estimated as follows. The $K\pi$ interaction has a range of typically 1 fm or less. The non-relativistic wave function outside the range is represented as

$$\phi_{out}(r) = N\frac{1}{r}exp\left(-\frac{\sqrt{2\mu E_B}}{\hbar c}r\right) \tag{1}$$

where N is the normalization constant, μ is a reduced mass of the $K\pi$ system and E_B is the binding energy. There is little knowledge of the wave function inside the interaction range although the contribution outside is dominant thus we can simply estimate the average radius as follows,

$$< r^2 >\sim \int r^2\phi_{out}^2(r)4\pi r^2 dr = \left(\frac{(\hbar c)^2}{4\mu E_B}\right). \tag{2}$$

For instance, $< r >$ is 4.3 fm for 5 MeV bound state and 2 fm for 30 MeV bound state. The present radius underestimates the real one since $\phi_{out}(r)$ is divergent at $r = 0$ although the real wave function is not. The obtained radius is fairly large compared to typical range of hadron interaction. This is an extended object thus appropriate momentum transfer to excite X is around 100 MeV/c or less. This small momentum transfer makes production cross section of X small. The low momentum transfer is particularly effective to produce X with small binding energy.

Based on the above consideration we propose here an experiment to search for X. It is the excitation of X by kaon beam irradiation on a proton and/or nuclear targets. The essential point of the reaction is its small momentum transfer. The momentum transfer of the $p(K^+, X^+)p$ reaction is shown in figure 1. The momentum transfer of the reaction at 0 degrees decreases gradually as an incident momentum P_K increases and becomes less

FIG. 1: Momentum transfer of the $p(K^+, X^+)p$ reaction at 0 degrees is shown for $m_X = m_K + m_\pi$ and $m_X = m_K + m_\pi - 30MeV$ case.

than 50 MeV/c at around 2 GeV/c. Since the spin-parity of K^+ and X^+ are 0^- and 0^+, respectively, the angular momentum transfer ($\Delta\ell$) has to be 1 for the proton target. This requires the momentum transfer of typically 200 MeV/c assuming that an interaction range is typically 1 fm. The angular distribution peaks at around 10 degrees for P_K=1 GeV/c. Therefore one can choose the incident K^+ momentum for experimental convenience. The use of nuclear target, however, may affect this choice. For instance, some $J^\pi = 0^+$ nuclei like ^{16}O have 0^- states then a 0^+ to 0^- transition in the target nucleus makes a kaon to X transition possible without angular momentum transfer. Thus momentum transfer as low as 50 MeV/c directly helps to produce X. Production of X through excitation of such nuclear states requires knowledge on a form factor which is left for future study.

X^+ produced by the $p(K^+, X^+)p$ reaction can be identified in an invariant mass spectrum obtained by measured momenta of K^+ and two γ's. In the present reaction there is an easier way. One measures K^+ momentum in coincidence with energetic two γ's. Only conceivable background is the reaction to produce π^0. This reaction gives K^+ momentum similar to that of X production. If two γ's are from X decay, the K^+ momentum is affected by momentum carried away by two γ's. On the other hand, the K^+ momentum is independent on two γ's if they are from the π^0 decay. The K^+ momentum is maximum when $K^+\pi^0$ invariant mass is just at the threshold. For instance, it is 0.72 GeV/c for 1 GeV/c incident K^+. On the other hand, the K^+ momentum can be as large as 0.96 GeV/c when two γ's are detected

backwards. The production cross section of X can be scaled to the production of $K\pi$ at low invariant mass region. Since π^0 production is clearly separated from the X production by detecting two γ's, abundant production of π^0 makes the search easy.

If X is proved to exist, Θ^+ is likely to be the $K\pi N$ bound state. Then the size of Θ^+ can give a rough estimate of the width. The decay can take place only when excitation of the s-wave to p-wave takes place in the πN system and the $K-\pi N$ system simultaneously. In order to realize the excitation, the three particles have to be present within the interaction range. The typical width for the strong interaction is around a hundred MeV. Then the decay width is

$$\Gamma \sim 100 \times \left(\frac{r_{int}}{r_\Theta}\right)^6 \mathrm{MeV} \tag{3}$$

where r_{int} is the interaction range and r_Θ is the radius of Θ^+. We take 1 fm as r_{int} which is the typical interaction range for the strong interaction. We currently use 2 fm for r_Θ where we assume that the binding energy of 30 MeV is carried by the pion. The actual size of Θ^+ should be larger since the binding energy is shared by three particles and weak repulsion between the kaon and the nucleon prefers configuration that they are apart. The width then becomes

$$\Gamma \sim 1\mathrm{MeV} \tag{4}$$

This estimate can be taken as an upper limit. We assume that if three particles are within r_{int}, the s-wave to p-wave transition takes place always which overestimates the width. Also facts that $K\pi$ interaction range (r_{int}) is probably smaller than 1 fm and r_Θ is probably larger then 2 fm underestimate the real size. Thus the width should be narrower than 1 MeV.

Recently reanalysis of the KN scattering data was carried out. It gave an upper limit of 1 MeV on the width of the K^+n resonance [14]. This estimate is much narrower than the upper limit experimentally obtained and hard to accept for the width of resonances in such a highly excited region. This analysis is consistent with our estimate of the width.

We have discussed the possibility to explain newly observed Θ^+ in terms of conventional pictures of the hadron physics. We discussed characteristics derived from the assumption that Θ^+ is explained as a bound state of $K\pi N$. It is plausible that $u\bar{u}$ and $d\bar{d}$ combinations in the chiral soliton model has strong relations to the pion field. Since mass of Θ^+ is close to that of $K\pi N$, one has to consider the relation of Θ^+ to a bound state of these three particles.

This leads to the existence of the proposed $K\pi$ bound state we call X. This possibility is very exotic and probably hard to believe although we show that current data may still allow such possibility. We think the strongly attractive $K\pi$ interaction is vital to reproduce Θ^+ as a bound state. We present an experiment to search for X. If no bound state is proved to exist, it is unlikely that Θ^+ can be explained as a bound state of the three particles.

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[1] T. Nakano et al.,Phys. Rev. Lett. 91 (2003)012002

[2] V. V. Barmin, et al. (DIANA collaboration): hep-ex/0304040

[3] S. Stepanyan, et al. (CLAS collaboration): hep-ex/0307018

[4] J. Barth, et al. (SAPHIR collaboration): hep-ex/0307083

[5] D. Diakonov, V. Petrov, and M Polykov, Z. Phys. A359 (1997) 305

[6] R. A. Arndt, I. I. Strakovsky, R. L. Workman and M. M. Pavan, Phys. Rev. C52 (1995) 2120.

[7] K. Hashimoto, Phys. Rev. C29 (1984) 1377.

[8] R. A. Arndt, L. D. Roper P. H. Steinberg Phys. Rev. D18 (1978) 3278.

[9] P. Estabrooks et al., Nucl. Phys. B133(1978) 490

[10] P. Bicudo and M. Marques, hep-ph/0308073

[11] F. Estrada, E. Oset and V Mateu, nucl-th/0311020

[12] T. E. O. Ericson, B. Loiseau and A. W. Thomas, Nucl. Phys. A663 (2000) 541c

[13] C.B. Dover, G.E. Walker, Phys. Rep. 89 (1982)1

[14] R. A. Arndt, et al., nucl-th/0308012